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Upper Ocean Observations Across an Arctic Transect

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The ability to identify and quantify seasonal and interannual temperature and salinity variations in the Arctic Ocean is critical to detecting warming trends, understanding circulation, and observing water mass movements. The SCICEX tests are currently addressing these issues. One phase of the SCICEX-95 test, conducted during April of 1995, allowed for a Transarctic snapshot of the upper water column. The transect lasted for eight days and extended approximately 1400 nm over the Arctic Ocean central basin, from near Pt. Barrow Alaska (72.05°N, -149.88°W) to Franz Josef Land (85.33°N, 51.3°E). Sixty-eight submarine launched, under ice, expendable conductivity, temperature, and depth (SSXCTD) probes were deployed at the rate of one probe approximately every 20 nm.

The shallow (40 m) mixed layer at the westernmost end of the track, between the Canada Abyssal Plain and the Northwind Ridge, displayed the warmest, least saline surface water. Below this layer, the halocline layer exhibited a dramatic 3.0 psu salinity gradient over 35 m depth. This gradient coincided with a 0.5°C temperature duct that extended to near 150 m. Additionally, salinity gradient variations produced stair-step like features at 200 m and 300 m depths. The transects coldest, least saline water was found between 200 and 450 m.

Proceeding eastward from the Northwind Ridge to the Alpha Ridge, salinities in the upper 300 m gradually increased, whereas the halocline decreased. Temperature values from the surface to depth exemplified the data mean, while their structures mimicked the profiles to the west. Over the Alpha Ridge, the mixed layer deepened to near 100 m and the upper temperature duct disappeared. A sharp 2°C temperature increase was observed between 100 and 300 m. Profiles at the northeastern end of the transect contained the coldest / deepest upper mixed layer (125 m) followed by a dramatic temperature increase (4°C / 100 m). Atlantic Intermediate Water was observed between 200 and 900 m and extended from west of the Lomonosov Ridge to the Barrents Plain.

Analyses of profiles collected during this test have allowed us to identify upper Arctic ocean features, boundaries, and water masses. However, to fully understand short term Arctic climatological variations, additional data are needed.

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Evaluation of the SSXCTD Fall Rate Equation

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The submarine launched, under ice, expendable conductivity, temperature, and depth (SSXCTD) probe was introduced by Sippican Corporation in 1993. Since then, there has been controversy over the data quality and the correctness of measurements collected. SSXCTD data, collected in the Arctic Ocean during summer of 1993 and spring of 1995, were used to evaluate the manufacturer's fall rate equation (FRE). SSXCTD depth is inferred from elapsed time by the fall rate equation; **Depth(m) = bt + at^2**, where depth is in meters, **t** is time in seconds commencing from the first measurement, and coefficients **a = -0.002 m s-2** and **b = 5.5 m s-1**.

SSXCTD temperature and salinity profiles were compared to nearby data obtained from a surface launched, mechanical, Seabird CTD. Data from the two field tests provided eleven Sippican SSXCTD / Seabird CTD profile pairs; six pairs from 1993 and five from 1995. Comparison among all data showed that the SSXCTD FRE consistently overestimated temperature and salinity features observed in concurrent CTD casts. Errors in SSXCTD depth estimates linearly increased with water column depth. SSXCTD offsets ranged from 35 m, at 100 m depth, to as much as 200 m, at 500 m depth, with the SSXCTD overestimating CTD depths by an average of 30%.

To quantify depth errors, a set of features common to both profiles were identified and their depths were noted. The time it took for the SSXCTD to reach the CTD's feature depth was found and revised **a** and **b** coefficients were computed. A mean coefficient was calculated for each profile and a single value representing each data set was obtained. The 1995 data yielded an improved FRE of **Depth = 3.95284 t -0.0007182 t^2 +12.16**. Identical steps were followed for the 1993 profile data and resulted in a slightly different set of best-fit coefficients.

Comparison of the best-fit coefficients calculated for each probe to their cooresponding batch numbers suggests a correlation between coefficients and batches. Nevertheless, applying the new FRE greatly improved the overall fit of SSXCTD to CTD data. Adjusted SSXCTD profiles are in good agreement with known features observed in historical data. However, additional data and further investigations are required to reduce the uncertainties associated with the FRE coefficients.

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Observed Anomalies in an Upper Arctic Transect

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Physical and acoustic data collected in the Arctic since 1990 is causing us to revise our understanding of Arctic Ocean circulation. Despite the key role Arctic processes play in global climate, our knowledge of Arctic water mass structure is still based on sparsely sampled measurements. The SCICEX program offers a unique and unprecedented opportunity because it will nearly double the number of transarctic oceanographic survey tracks, once completed. Data presented here represents one phase of the SCICEX-95 experiment during which under ice, submarine launched, expendable CTDs (U/I SSXCTD) and surface launched, mechanical CTDs were deployed approximately every 45 km over a 2500 km track from Pt. Barrow Alaska to near Franz Josef Land. These profiles were compared to GDEM and POLEX modeled climatologies, as well as historical measurements from the 1970's to 1990's.

Analysis of the SCICEX-95 transarctic data showed that warmer Atlantic Intermediate Water (AIW) in the Eastern Arctic occupied a larger area than was historically known. This data exhibited an intensification and shifting in the front between Atlantic and Pacific waters from near the Lomonosov Ridge toward the Makarov Basin. Warm water cores were observed in the upper AIW water near the leading edge of this frontal region and over the Northwind Ridge to the west. The warm cores extended 200 m vertically, 100-300 km horizontally, and coincided with the location of topographic ridges. These warm cores are characterized by 1 deg C warmer temperatures than found in historical data. Numerous thermohaline inversions were also observed in the AIW. These inversions extended 100 km horizontally, 50 to over 200 m vertically, and were aligned with constant density surfaces.

Downwelling of colder Arctic Surface Water (ASW) was observed over the Mendeleyev and Canadian Basins. The upper 100 m of ASW east of the Northwind Ridge displayed a 3 psu increase in salinity compared to historical data, while a 3 psu decrease was observed to the west of this ridge. Similarly, temperatures in the ASW were over 1 deg C colder

east of the Lomonosov Ridge, and approximately 1 deg C warmer west of the Northwind Ridge. These observed perturbations are too large to be attributed to seasonal and interannual variability, and most likely correspond to a change in the Arctic Ocean circulation driven by an increase in temperature and movement of incoming North Atlantic water.

Measured transarctic acoustic travel times and model comparisons

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Abstract

Absolute travel times and interarrival times of the modes propagated across the Arctic during the Transarctic Acoustic Propagation (TAP) experiment in April 1994 differ significantly from modelled travel times using historical climatology. Recent CTD measurements taken by icebreakers in August 1994 and by the submarine USS Cavalla (SSN-684) in April 1995 show an intrusion of warmer Atlantic Intermediate Water in the Eastern Arctic and beyond the Lomonosov Ridge in the Makarov Basin in contrast to the historical climatology. Modelled travel times and interarrival times using these data agree more closely with measured results. The increase in temperature inferred from the observed travel time change between the data and the model using the historical climatology is consistent with the new CTD measurements. These results demonstrate the value and potential of acoustic thermometry as an effective strategy for long-term synoptic observations of temperature changes on the Arctic Ocean.

1. Introduction

The TAP Experiment propagated acoustic transmissions at 19.6 Hz over 2600 km from a Russian/U.S. ice camp north of Spitzbergen ("Turpan") to a U.S. ice camp in the Beaufort Sea (SIMI for Sea Ice Mechanics Initiative) and 900 km to a U.S./Canadian ice camp in the Lincoln Sea ("Narwhal"), shown in Fig. 1. The experiment not only showed that it is possible to measure the integrated temperature change along the path with a precision approaching 0.1 millidegrees C; it also detected average warming along the path in the Atlantic Intermediate Layer (200-700 m depth) of approximately 0.4°C [1,2]. This temperature change was inferred from observed differences in the travel time of acoustic mode 2, which is most sensitive to temperature changes in the AIW layer [1], as compared to that predicted using historical climatology. Direct measurements using CTD's deployed from icebreakers has shown an increase in temperature of the Atlantic Intermediate Layer in the Makarov Basin [3,4,5] and in the Eastern Arctic [4,5] when compared to earlier measurements. This result was affirmed again in April 1995 during the cruise of the submarine USS Cavalla during the SCICEX '95 experiment in which sixty-eight submarine launched, under-ice, expendable conductivity, temperature, and depth (SSXCTD) probes were deployed on a track from the Beaufort Sea to Franz Josef Land [6]. These new

measurements showed temperature differences with the historical climatology that are consistent with the acoustically derived results of TAP. Using sound speed profiles from the Arctic Ocean icebreaker cruise of August 1994 (AO '94), and those we obtained from the SCICEX '95 cruise we have performed additional acoustic modelling that yield results that are in better agreement with the experimental measurements from TAP. The remaining differences between these new model results and the TAP data reflect the fact that the sound speed profiles from AO '94 and from SCICEX '95 were not exactly coincident with the TAP propagation track in space or time. However, it will be important for future experiments, that simultaneous measurement of SVP's along acoustic propagation paths be performed at least once, to provide a better baseline than we were able to achieve with the TAP experiment.

2. TAP MLS Data and Model Comparisons

During the TAP experiment 12 sets of maximal length sequences were transmitted. Each sequence consisted of a repetition of a 127, 255, 511, or 1023 digit code for an hour. The first two MLS transmissions used 25 cycles of the 19.6 Hz carrier frequency, per digit, while the remaining 10 used 12.5 cycles per digit. The MLS data were beamformed on the thirty-two element horizontal array deployed at the SIMI ice camp, replica matched filtered and the arrival times for modes 1-4 were obtained from the pulse compressed peaks. Because of it's much higher scattering losses mode 1 was not observed on four of the MLS transmissions. Mode 4 was not detected on one of the MLS transmissions. The source transmissions were regulated by a Rubidium oscillator, which was manually synchronized to absolute GPS time at the beginning of the experiment, and once again after a loss of oil pressure in the camp generator forced a shutdown of all electronic equipment. The range between the source and receiver camps was determined by GPS for each of the 12 MLS transmissions. Using the known range and the measured travel times for each mode of each MLS sequence an average modal group velocity was computed and an average arrival time and standard deviation of arrival time for each mode was computed for a nominal range of 2637.5 km (the actual range for transmission #23, a 255 digit MLS). These results are shown in Table 1. The standard deviation of approximately 1 sec is a consequence of the fact that the start of each transmission was manually initiated. This was the single largest source of error in measuring the absolute travel times. The precision of

	Mode 1	Mode 2	Mode 3	Mode 4
TAP	1828.2 ± 1.1	1812.2 ± 1.2	1810.7 ± 1.3	1809.6 ± 1.0
GDEM	1829.2 (+1.0)	1814.5 (+2.3)	1811.3 (+0.6)	1810.5 (+0.9)
AO '94	1828.3 (+0.1)	1812.1 (-0.1)	1811.4 (+0.7)	1810.6 (+1.0)
AO/SCI	1829.4 (+1.2)	1813.9 (+1.7)	1811.8 (+1.1)	1810.8 (+1.2)

Table 1: Absolute modal travel time seconds.

measuring the time of a peak was better than a few hundredths of a second [7].

Also shown in Table 1 are the predicted arrival times of each of the modes using three different sets of 26 SVP's along the TAP propagation path from Turpan to SIMI (Fig. 1). The

numbers in parentheses are the differences in seconds of the observed TAP travel times and the model results. The GDEM (Generalized Digital Environmental Model [8]) set was produced by the Naval Oceanographic Office from data collected by the Navy in the Arctic through the 70's and early 80's. These data represent the historical climatology. For each of the 26 points along the TAP path the GDEM SVP from the appropriate province was taken. The AO '94 set was constructed using data taken by a joint U.S. and Canadian icebreaker cruise across the Arctic Ocean in August 1994 (Fig. 1) [4,5]. Because the AO '94 cruise did not go into the deeper parts of the Beaufort Sea except for one station, this one station was used for most of the Beaufort Sea in this set. The AO/SCI set consists of a combination of the AO '94 SVP's for the Eastern Arctic and just across the Lomonosov Ridge, and SVP's obtained from the SCICEX '95 submarine cruise in April 1995 (Fig. 1), for the Beaufort Sea. For both the AO '94 set and the AO/SCI set the actual SVP's measured at Turpan and SIMI were used. A coupled normal mode code was used to generate the modal arrival times at 19.6 Hz for each of the three sets of SVP's.

The AO '94 set is closest to the TAP data, while the AO/SCI set predicts a faster mode 2 than the climatology and is in closer agreement with the TAP data, but inexplicably, is closer to the GDEM climatology for the other modes. The consistent offset of modes 3 and 4 from the data for all three sets of SVP's could indicate that there is an unknown timing error in the TAP data of .6-.7 secs. Since the deeper waters are presumably more stable, and since modes 3 and 4 sample these deeper waters (>700 m) agreement should be better. Even if this offset were added to the TAP travel times, mode 2 from TAP is still over 1.5 secs faster than that predicted by the climatology, supporting the conclusion that the AIW layer in the Arctic has warmed over the last 5-10 years.

Calculation of the modal interarrival times from the 12 MLS transmissions was also performed. This provides a more robust comparison since this measure is independent of absolute timing errors from one MLS sequence to the next. These results are shown in Table 2,

	Mode 1-2	Mode 2-3	Mode 3-4
TAP	16.21 ± 0.15	1.48 ± 0.11	0.87 ± 0.07
GDEM	14.71 (+1.50)	3.22 (+1.74)	0.77 (-0.10)
AO '94	16.13 (-0.08)	0.68 (-0.80)	0.76 (-0.11)
AO/SCI	15.57 (-0.64)	2.07 (+0.59)	0.99 (−0.12)

Table 2: Interarrival times of the modes in seconds.

and compared with the predicted interarrival times from the GDEM climatology and the two more recent SVP measurements. Note the consistency of the interarrival times from the TAP data as indicated by the small standard deviations. The agreement of the data and all of the models with the interarrival time of modes 3 and 4 indicates consistency of the deeper part of the SVP's in the models with the TAP data, not observed with the absolute travel times. Clearly the newer data sets are in better agreement with the data for the interarrival times between modes 1 and 2, and between modes 2 and 3. As in Table 1 the numbers in the parentheses are the time differences in seconds of the interarrival times compared with the TAP observations. The difference between the GDEM times and the AO '94 and AO/SCI times is a result of the faster arrival time of mode 2 which is consistent with the observations.

3. Conclusions

Measurements of increased temperature in the AIW layer of the Arctic Ocean from icebreakers and submarine are consistent with the observed modal travel times of the TAP experiment in April 1994. Whether this is a "normal" cyclical phenomena or an indicator of a long term secular trend is unknown. CTD data in the Arctic Ocean is aliased in time and very sparse in space, making definitive evaluation of even interannual cycles difficult. The need for a system of continuous monitoring is evident. Acoustic thermometry can provide such long term continuous observations. Simultaneous SVP's should be taken initially, to establish a reliable baseline for acoustic monitoring paths.

4. Acknowledgements

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References

[1] P. N. Mikhalevsky, A. B. Baggeroer, A. Gavrilov, and M. Slavinsky, *Experiment Tests Use of Acoustics to Monitor Temperature and Ice in Arctic Ocean*, Eos, Transactions, American Geophysical Union, **76** (1995) 265, 268-269.

[2] P. N. Mikhalevsky, A. B. Baggeroer, A. Gavrilov, and M. Slavinsky, *CW and M-Sequence transmissions across the Arctic*, J. Acoust. Soc. Am., **96** (1994) 3235.

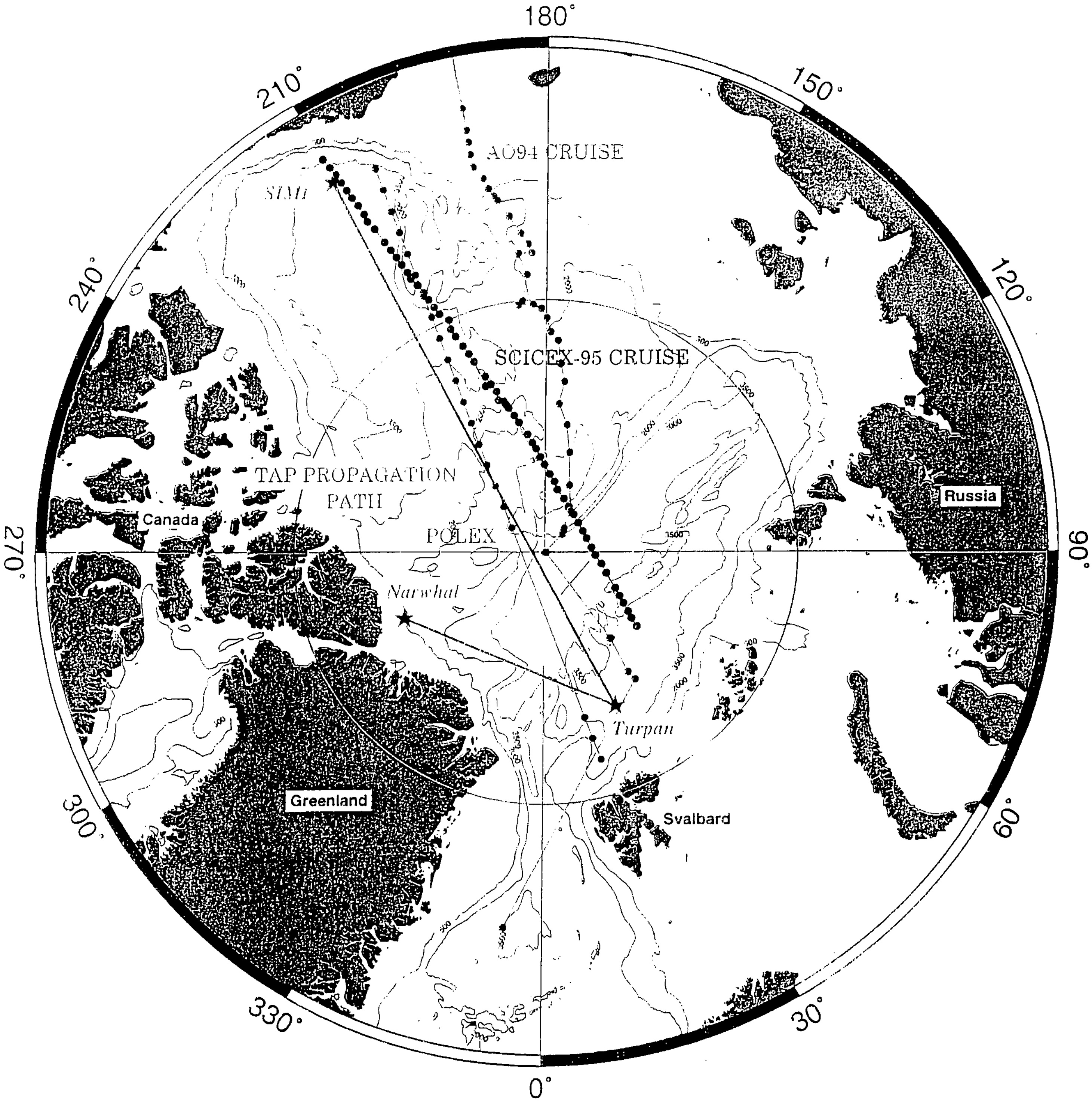
[3] E. C. Carmack, R. B. Macdonald, R. G. Perkin, F. A. McLaughlin, and R. J. Pearson, *Evidence for warming of Atlantic water in the southern Canadian Basin of the Arctic Ocean: Results from the Larsen-93 expedition*, Geoph. Res. Ltrs., **22** (1995) 1061-1063.

[4] E. C. Carmack, K. Aagaard, J. H. Swift, R. G. Perkin, F. A. McLaughlin, R. W. Macdonald, E. P. Jones, J. N. Smith, K. Ellis, and L. Kilius, *Large thermohaline changes in the Arctic Ocean*, Nature, submitted (1995).

[5] K. Aagaard and E. C. Carmack, quoted in *Taking a Bottom-to-Sky "Slice" of the Arctic Ocean*, Science, **266** (1994) 1947.

[6] R. Keenan, L. Merriam, M. S. Moustafa, and P. N. Mikhalevsky, *Upper Ocean Observations Across an Arctic Transect*, American Geophysical Union, Ocean Science Meeting, San Diego CA, 12-16 Feb. 1996.

[7] A. N. Gavrilov, and P. N. Mikhalevsky, *Phase acoustic tomography with broadband signals in the Arctic*, 3rd European Conference on Underwater Acoustics, Heraklion, Crete, Greece, 24-28 June 1996.



— TAP EXPERIMENT APRIL 1994
— U.S./CANADIAN ICE BREAKER CRUISE, A094, AUG. 1994
— U.S.S. CAVALLA (SSN-684), SCICEX-95, APRIL 1995
— POLEX RUSSIAN MODELED DATA 1955-1956, 1973-1979

Figure 1. Selected Arctic locations